

Ocean biogeochemistry in the framework of “climate engineering”

Abstract

Climate Engineering employs technical methods to mitigate climate change without lowering anthropogenic CO₂ emissions. One of these methods, the artificial increase of ocean alkalinity, has been proposed to enhance the oceanic uptake of atmospheric CO₂ and counteract the on-going ocean acidification. We used a global biogeochemical model to show that artificial ocean alkalinity input must be 200 times higher than the input by natural weathering flux to hold the global seawater pH close to today's value. The effects on ocean biogeochemistry would be substantial.

Ocean biogeochemistry

The ocean contains substances like carbon, nitrogen, oxygen and phosphorus. They determine the composition of seawater and affect Earth's climate by a number of physical, biological, chemical and geological processes. The field of ocean biogeochemistry examines the cycles of these substances and their interaction with other components of the Earth system. Due to the risen greenhouse effect of atmospheric carbon dioxide (CO₂), questions regarding the carbon cycle received augmented scientific attention over the last decades (e.g. IPCC [1]). The ocean exchanges CO₂ with the atmosphere and acts along with the terrestrial ecosystems as the most important CO₂ sink, when atmospheric CO₂ concentrations are increased over extended periods. On short time scales, CO₂ and the nutrients phosphorus and nitrogen of plants (phytoplankton) are bound in the ocean surface and are transported to the deep ocean. The total amount of carbon dissolved in the ocean is approximately 50 times higher than the atmospheric carbon concentration, and about 20 times higher than the carbon stored in soil.

Present and future changes

The Max Planck Institute for Meteorology (MPI-M) uses a global Earth system model (MPI-ESM) since many years. The physical core of the model consists of general atmosphere-ocean circulation models. These models provide circulation patterns for the global ocean biogeochemistry component HAMOCC, which simulates ecosystem processes as well as biogeochemical tracers in the oceanic water column and in the sediment (Maier-Reimer [2]; Ilyina et al. [3]). In cooperation with the German Climate Computing Center (DKRZ), MPI-M took part in consortium calculations for the international Coupled Model Intercomparison Project Phase 5 (CMIP5) and the Intergovernmental Panel on Climate Change (IPCC) with MPI-ESM.

The results of the CMIP5 simulations project a warming of the ocean by two to four degrees caused by anthropogenic CO₂ emissions until the end of the 21 century. In parallel, the oceanic carbon content increases (Fig. 1). The warming of the ocean causes the stratified water column to be more stable and the vertical mixing is slowed down. Thereby, the concentration of dissolved nutrients is reduced in the surface and as a result, the production of organic matter is reduced by up to 30% (Fig. 1).

This points to a fundamental change of the nutrient distribution and the carbon cycle in the ocean. CO_2 reacts with seawater and the oceanic uptake of atmospheric CO_2 causes the seawater to form more carbonic acid and to produce more hydrogen ions. As a consequence, the pH drops (Fig. 1), a process termed ocean acidification.

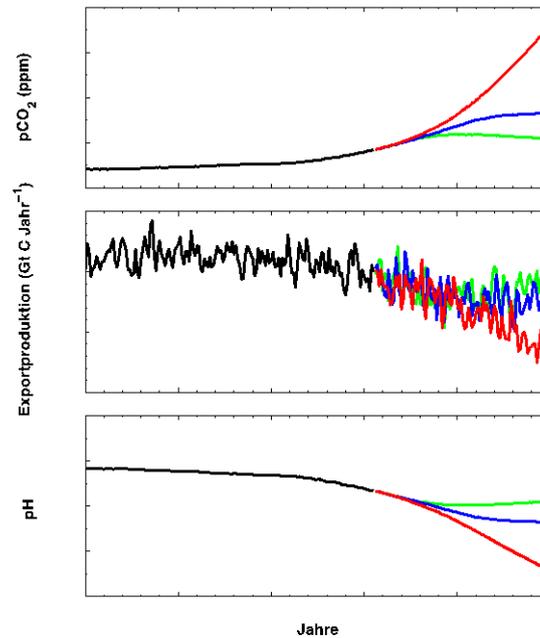


Fig. 1: Temporal evolution of oceanic $p\text{CO}_2$, export production and seawater pH, calculated in the IPCC simulations of MPI-M for historical period (black) and for future greenhouse gas concentration scenarios RCP8.5 (red), RCP4.5 (blue) and RCP2.6 (green).

The ocean surface has been a habitat with nearly constant chemical conditions at moderate pH values of approximately 8.2 ± 0.1 for about 2 million years (e.g. Gattuso and Hansson [4]). The ability of seawater to bind acids (total alkalinity - Total Alkalinity - TA) remained nearly constant during this period (Ilyina et al. [5]). The pH of seawater has already decreased by 0.1 units caused by the oceanic uptake of anthropogenic CO_2 and is projected to fall by 0.4 units by the end of the century. Ocean acidification also leads to a reduction of the marine carbonate concentration. Carbonate is needed for calcification and thus for the production and growth of calcite shells and calcareous skeletons. The saturation state of carbonate (Ω) shows that today's ocean has a high concentration of carbonate in the surface water (oversaturation, $\Omega > 1$; Fig. 2).

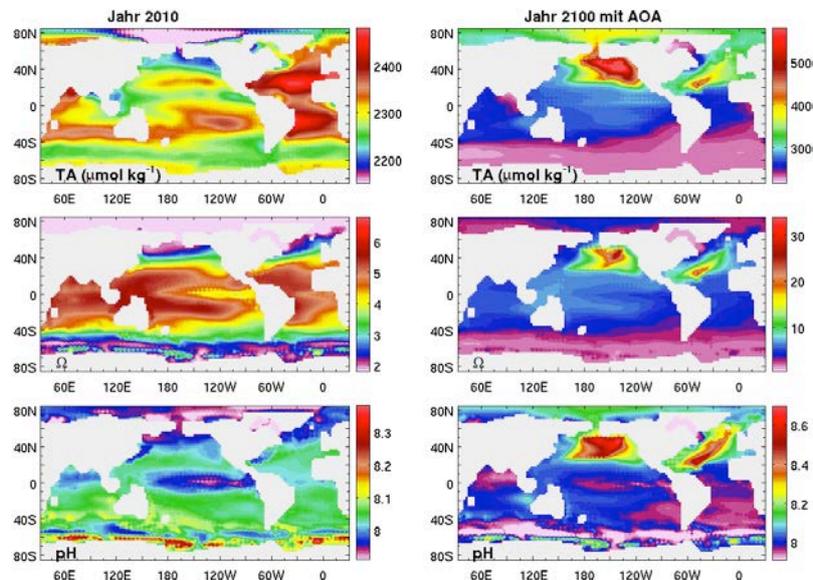


Fig. 2: Distribution of seawater pH, carbonate saturation state (Ω) and Surface Total Alkalinity (TA), calculated for the year 2010 and for a climate engineering scenario, in which ocean alkalinity has been increased in a 2:1 ratio to CO_2 emissions.

Less carbonate ions are available at low Ω and pH values, with the result that little or no calcium carbonate can be formed. Calcium carbonate even dissolves at undersaturation ($\Omega < 1$). We do not yet understand all the effects of these rapid changes in marine chemistry and temperature, but we expect several negative impacts on marine ecosystems, the food chain and biodiversity, as well as changes in the reproduction and physiology in marine organisms. Some of these effects have already been observed (e.g. Gattuso and Hansson [4]).

Ocean alkalinity enhancement forced by “climate engineering”

Over tens of thousands to hundreds of thousands of years, the anthropogenic CO_2 is neutralized by natural weathering - a process of effective CO_2 removal and thus a significant CO_2 sink. One method of climate engineering is the artificial acceleration of this process to remove CO_2 from the atmosphere. With this method, large amounts of carbonate or silicate are processed, ground and applied to land or dissolved in seawater (Shepherd et al. [6], Köhler et al. [7]). "Artificial Ocean Alkalinization (AOA)" addresses the reaction of calcium carbonate with CO_2 or with the production of strong bases (e.g. calcium hydroxide), followed by the exposition of the resulting dissolved substances to the sea surface (Kheshgi [8]; Rau [9]). These methods lead to an elevated oceanic TA and change carbonate chemistry. Thereby, the pH and Ω values and the ability of seawater to absorb and store atmospheric CO_2 are increased. The available literature only documents laboratory experiments on various artificial weathering methods, neither the global effectiveness nor the global environmental impacts of an artificial ocean alkalinity enhancement are proofed. Therefore, assessments of potential large-scale implementations are only possible on the basis of model studies.

Scenarios of oceanic alkalinity enhancement

We examined the artificial alkalinity enhancement (AOA) and its long-term effects using the biogeochemistry model HAMOCC by MPI-M (Ilyina et al. [10]). The input of alkalinity to the ocean was based on the anthropogenic CO₂ emissions in the moderate IPCC A1B scenario. A fixed ratio of alkalinity was applied for each mole of emitted ocean surface CO₂ from year 2020 on. We have studied different scenarios. Depending on the scenario, the molar ratio of alkalinity to CO₂ ranged from 0.2:1 to 2:1. The modeling results show that the input of alkalinity in relatively small amounts, for example in the ratio 0.2:1 (TA:CO₂), has little effects on the values of atmospheric CO₂ and oceanic pH (Fig. 3).

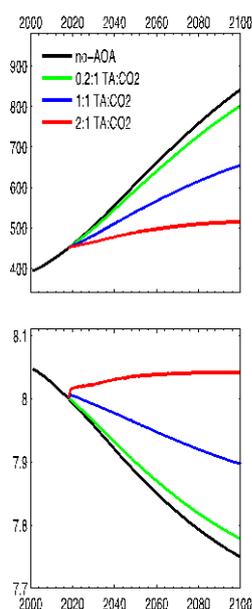


Fig. 3: Temporal evolution of atmospheric pCO₂ and pH values with and without oceanic alkalinity enhancement.

But we observed a significant effect when alkalinity is increased in a 2:1 ratio in an area of approximately 47 million km² in the Pacific and Atlantic Ocean (about one seventh of the ocean). The atmospheric CO₂ would be less than 520 ppm by the year 2100, instead of 840 ppm without AOA. The global mean surface pH value would be reduced by less than 0.1, instead of 0.4 without AOA. This scenario, however, would require an input of about 2400 billion mol alkalinity per year. The global natural weathering causes an input of approx. 12 billion mol alkalinity per year. Thus, a global artificial alkalinity enhancement of this type equates the acceleration of natural weathering by a factor of 200.

Furthermore, our results indicate that the input of alkalinity in large quantities would significantly interfere with the distribution of biogeochemical parameters (Fig. 2). In the 2:1 scenario, for instance, the total surface alkalinity is expected to increase to more than 5500 mol kg⁻¹ in regions where alkalinity is put in. In addition, the calcite saturation (Ω) would increase to more than 30, considerably above the naturally occurring level, which is in the range between about 4 and 6 at the present ocean surface.

It is expected that seawater pH values would rise up to 8.7 at sites of alkalinity addition. It would take some time before ocean currents would distribute the alkalized water to a larger volume and thereby reduce the alkalinity input.

In summary, only scenarios with a large amount of alkalinity in large marine areas have the potential to increase the oceanic uptake of CO₂ from the atmosphere and reduce further ocean acidification on a global scale. Such processes would enhance the biogeochemical parameters pH and Ω significantly over natural levels and would be harmful to marine life. Therefore, no alternative to the reduction of CO₂ emissions can be deduced from our results in order to limit climate change and ocean acidification. However, the local application of the climate engineering method AOA might be considered for highly valuable ecosystems to mitigate the negative effects of ocean acidification.

References

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Contact:

Dr. Tatiana Ilyina
Max Planck Institute for Meteorology
Phone: (+49) 40 41173 164
Email: tatiana.ilyina@zmaw.de

Dr. Annette Kirk
Max Planck Institute for Meteorology
Communication
Phone: (+49) 40 41173 374
Email: annette.kirk@mpimet.mpg.de